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Cold Atom Lab 2005-2007 Update

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14. ABSTRACT
The Cold Atom Research Laboratory at Hanscom AFB is investigating the fundamental physical limitations as well as the practicality of developing precision rotation sensors using the interference of alkali atoms in dilute gases. Atoms that have been laser cooled can have their momentum reduced to the point that they form a Bose-Einstein condensate, which can be 10 orders of magnitude more sensitive to rotation than a light-based interferometer. We have designed a 4-Wire Off Axis Microchip Ringtrap. A partially circular magnetic waveguide centered between all four wires is maintained by running counter-propagating current through either pair or all four wires. While the current is ramped down in the outer pair, the current is ramped up in the inner pair, so that the waveguide maintains its shape near the minimum where the atoms travel.

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1. Introduction to chip based interferometry

The Cold Atom Research Laboratory in the Space Vehicles Directorate of AFRL at Hanscom Air Force Base is investigating both the fundamental physical limitations as well as the practicality of developing precision rotation sensors using the interference of alkali atoms in dilute gasses.

Atoms that have been cooled, specifically laser cooled, can have their momentum reduced to the point that their wave-like quantum behavior becomes observable with macroscopic devices such as a CCD camera. In the case of a boson, such as ^{87}Rb, if all the critical parameters are met, the atoms will form a Bose-Einstein Condensate. In this case, the entire ensemble or condensed cloud has a single wavelike identity with an associated quantum phase. In an analogous manner of a light interferometer the BEC can be split and re-combined to enclose area and if the path lengths are different the resulting recombination results in a phase difference. This phase difference is directly related to the path length difference, which for the case of a Sagnac interferometer measures the rotation rate.

The sensitivity of light based interferometers is limited by the ability to work with smaller wavelengths and the speed of the light. If a direct comparison is made between a typical light based interferometer and that of an atom interferometer, the atom interferometer is about 10 orders of magnitude more sensitive than the light based interferometer. However, light based interferometers have a high flux of particles and efficient methods of splitting and recombination. Our research is trying to determine the fundamental physics related to creating a practical atom rotation sensor and understanding the quantum mechanical underpinnings to map out the practicality of this new technology.

Other considerations that must be taken into account when performing atom interferometry is the scalability, cost, weight, power consumption, as well as others. In the late 90's Mark Kasevich's group demonstrated an atom interferometer[1-2] using a thermal atom beam exiting an oven, with accuracies greater than the state of the art fiber optic gyroscopes. However, a beam experiment has a highly collimated beam with large longitudinal velocity and because rotation sensitivity scales with the area enclosed and the transverse velocity achieved by splitting is so small, the atoms needed to travel six meters in order to enclose a sufficient area (see Figure 1).

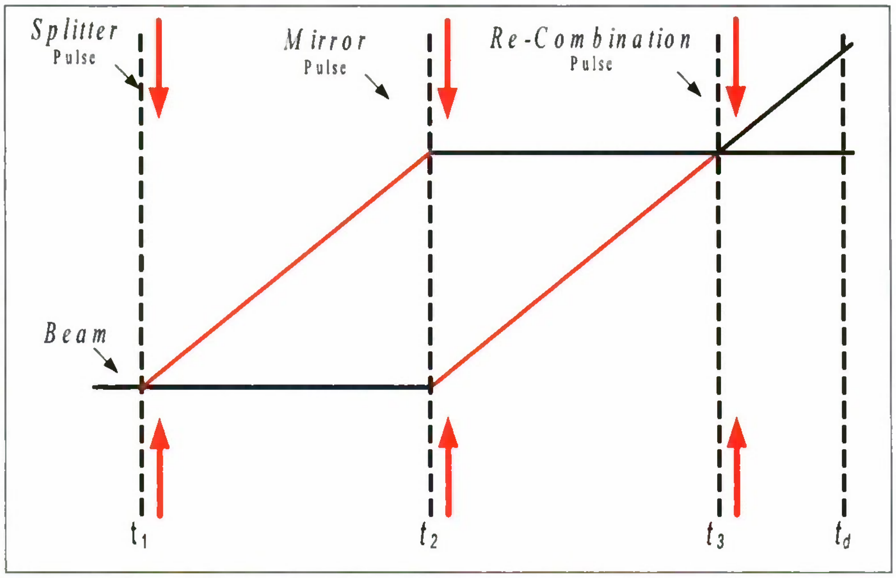

Figure 1. Illustration of the thermal beam experiment, the path separation is exaggerated for clarity.

A device this large may be workable for large vehicles like submarines however; there is a demonstrated requirement for highly accurate gyroscopes that are much smaller. Fortunately, progress in magnetic trapping of cold atoms has shown that these atoms can be confined by relatively weak potentials produced by thin current carrying wires. Advances in microchip fabrication can be leveraged to make intricate wire geometries on a microchip and the opportunity to build a low power and compact device is now possible. We have chosen to study a circular geometry in our experiments and what follows is an update on the progress we have made.

2. 4-Wire Off-Axis Ringtrap Microchip

2.1 Design

On or about June 2005 we received the 4-Wire Off Axis Microchip Ringtrap. This microchip follows the design laid out in US Patent 7,030,370 B1 (April 18, 2006), by our group and the working of the microchip was discussed in the Journal of Physics B: Atomic, Molecular and Optical Physics, 38 (2005) pg 3289-3298[3]. The chip's Ringtrap is provided by 4 circular leads of differing radius. There are two pairs of wires that terminate either to the edge of the microchip or to the center, the latter is energized by vias (small gold filled windows in the chip). The main motivation for having two sets of leads is to avoid waveguide imperfections generated by the input leads to the circular wires.

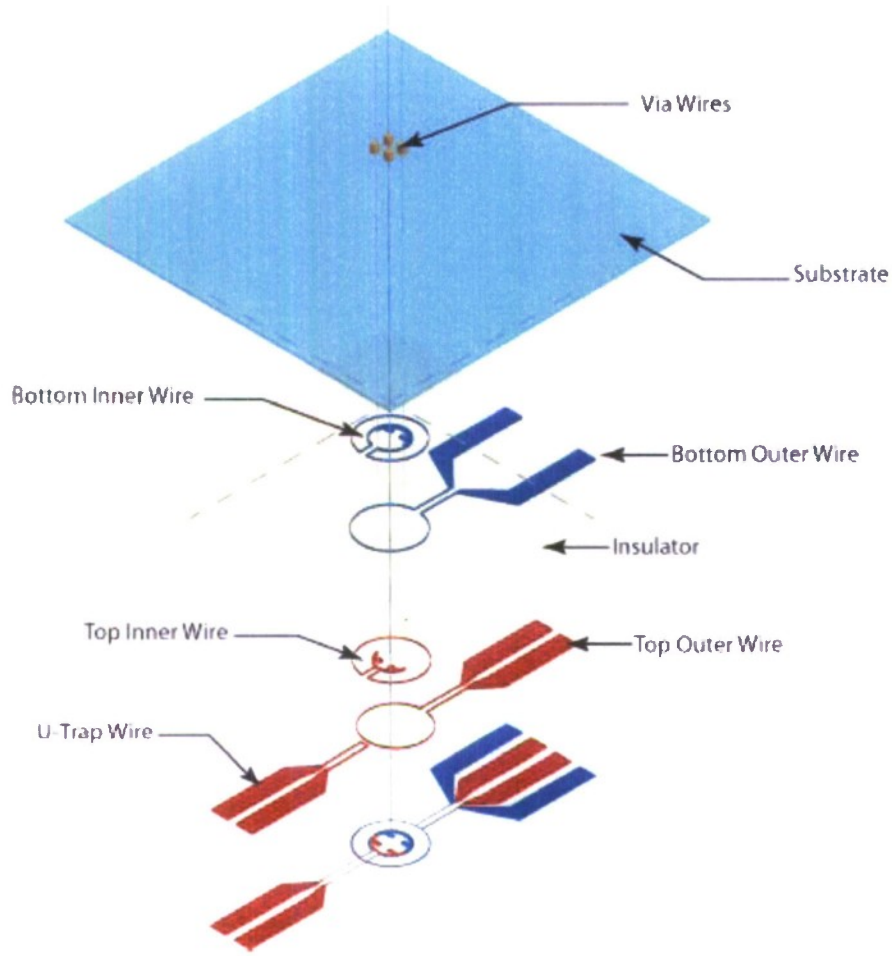

Figure 2. Exploded view 4-Wire Off -Axis Ringtrap Microchip.

A partially circular magnetic waveguide centered between all for wires is maintained by running counter-propagating current through either pair or all four wires. Each pair of wires consists of an upper and lower wire, where the lower is offset at an angle, see Figure 3. The inner and outer wire pairs provide an overlapping waveguide allowing the waveguide to be maintained as the atoms approach either the 12 o'clock or 6 o'clock position.

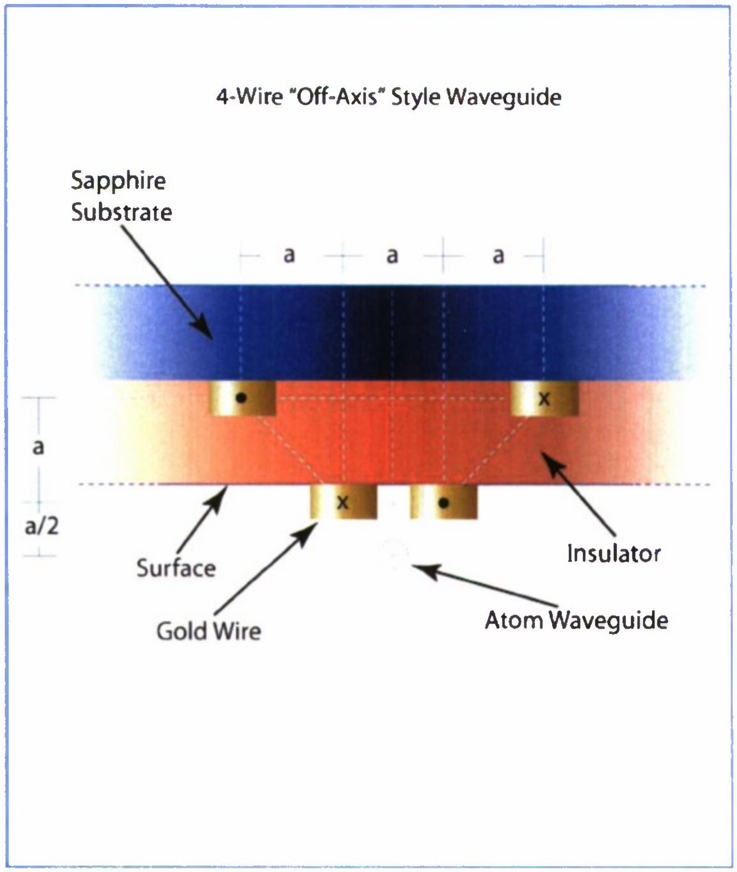

Figure 3. Cut-Away view of the 4-Wire Off-Axis Ringtrap Microchip.

Operation

As mentioned earlier, it is imperative to avoid the perturbations in the waveguide generated by the leads of the wires. To do so, the leads are switched from the outer pair to the inner pair as the atoms travel from below the 6 o'clock positions to the 12 o'clock positions. In this way the waveguide remains smooth in the atoms frame of reference and the transition from outer to inner leads can be made without perturbations. A sequence of transfers are shown below; as the current is ramped down in the outer pair, the current is ramped up in the inner pair. At the mid-point both pairs are energized at half their maximum value. What is important in Figures 4 and 5, is that the waveguide maintains it's shape near the minimum where the atoms travel.

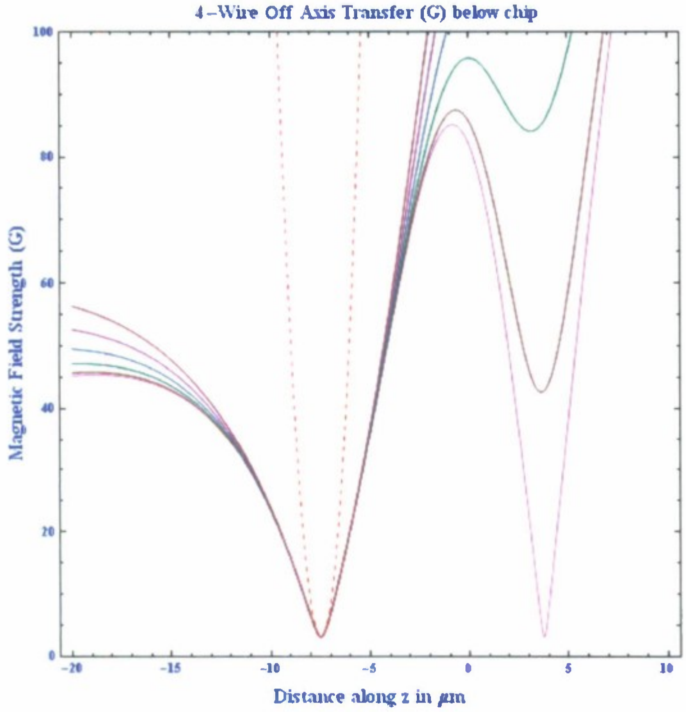

Figure 4. 4-Wire Off-Axis Ringtrap Magnetic Field Strength along z-Axis during transfer. Each color represents a different time step, where the current was linearly ramped down (up), for the outer (inner) leads.

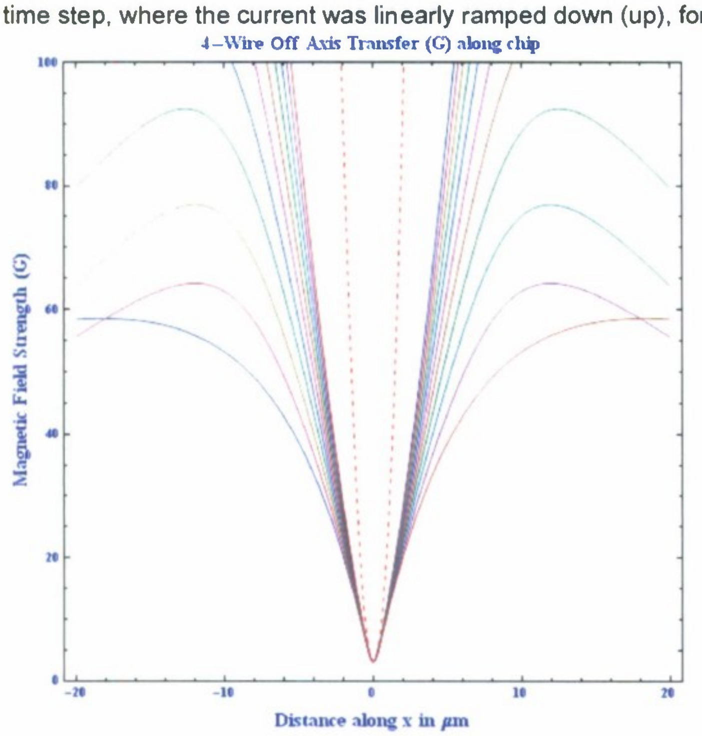

Figure 5. 4-Wire Off-Axis Ringtrap Magnetic Field Strength along x-Axis during transfer. Each color represents a different time step, where the current was linearly ramped down (up), for the outer (inner) leads.

A contour plot also demonstrates the location of the waveguide minimum at the mid-point of the transfer. The atoms chosen for these experiments are deflected towards the minimum of the magnetic field gradient and the atoms are confined in a "tube-like" ring.

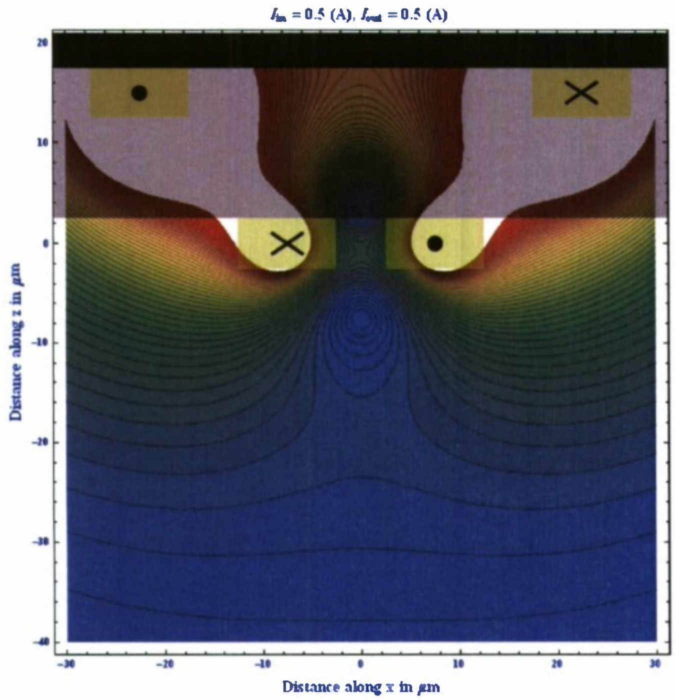

Figure 6. Contour plot of the magnetic field strength with all 4 wires on at half their maximum current.

3. Results

The fabrication of the Microchip took place at the AFRL/RYDD Sensors Directorate at WPAFB. The wires were gold electroplated on a 2 × 2 cm sapphire substrate. The distance of the waveguide to the chip was (7.5μm) chosen for the tightest confinement for the smallest current. We discovered along with other groups in our field that this "close" proximity to the surface of the chip caused problems. Among the more serious problems were the number of thermal photons generated by the heat produced in the substrate. In particular, photons in the frequency range that can cause atoms to cascade into an un-trapped "high-field" seeking state scale up as the atoms are trapped closer to the microchip. For the normal operating conditions of this chip, where the atoms are 10 to 15 microns from the chip's surface, the lifetime of the atom cloud or BEC is short when compared with the time necessary to make a rotation measurement. Another issue that arose with proximity is fragmentation. Fragmentation occurs when the cloud/BEC begins to break into distinct spatial regions resulting in the loss of well defined global phase, the entity that allows us to measure rotation so sensitively. The fragmentation appears when the waveguide has small imperfections that are large enough to trap or prevent the atoms from freely traveling around the waveguide. It is thought that imperfections and defects in the wires create small non-uniform currents that are not averaged out at close proximity.

A third issue with proximity (<100 microns from the surface) involves splitting and re-combining the atoms. Since we need the phase information, the splitting needs to be coherent. Thus we plan to use Bragg Scattering. Bragg Scattering involves two counter-propagating double pulses of light and acts as a diffraction grating. The atoms are split into a superposition of two opposite momentum states with momenta of $\hbar k$, where k is the wavenumber of the light pulses and $\hbar$ is Planck's constant. It has been recently determined that there are practical limitations as to how closely this coherent splitting can be done to the surface of a chip. The beam waist of the Bragg pulse is limited by the distance from the atom cloud to the chip

surface in order to avoid interference due to reflections of the laser pulse off of the surface of the chip. In addition to the above mentioned problems with this chip design is the relatively low heat conductivity of the sapphire substrate. This prevents the use of higher currents in the wires on the chip. The number of unexpected issues that we discovered along with the difficulty of fabricating a new chip every time an issue was discovered, prompted us to develop a method to streamline the process of design and testing in the lab. We began a new collaboration with AFRL/RYHC here at Hanscom AFB and took a more active role in the fabrication and design of the microchips.

It is worth noting that Bouchoule et. al.[4-5] has found a solution to the fragmentation issue. The procedure is to use AC instead of DC for the waveguide. If the current and magnetic fields modulate at the proper frequency the atoms "see" a static waveguide, however, the defects become averaged out allowing the BEC to propagate freely.

4. Science System

4.1 New Chip Cell

We designed a new chip cell that standardized the connections and alignment of our microchips. This standardization simplifies our microchip designs and should shorten our turn-around time between chips.

The new chip cell incorporates a hand blown glass structure attached to a 30-pin Ultra-High Vacuum feedthrough. A COTS UHV feedthrough provides the necessary maintenance of the ultra-high vacuum (10-12 Torr.) needed for these experiments. Cold atom experiments typically have competing design requirements. To ensure the experiment begins with as many cold atoms as possible, the collection stage (Magneto-Optical Trap) requires a large quantity of background gas. However, once the atoms are in the waveguide, the atom lifetime is limited by the background gas collisions. We manage these conflicting requirements by dividing our experiment into two physically separated areas that are differentially pumped. The atoms are collected in the MOT Area and transported to the Science Area via magnetic transfer coils, see Figure 7.

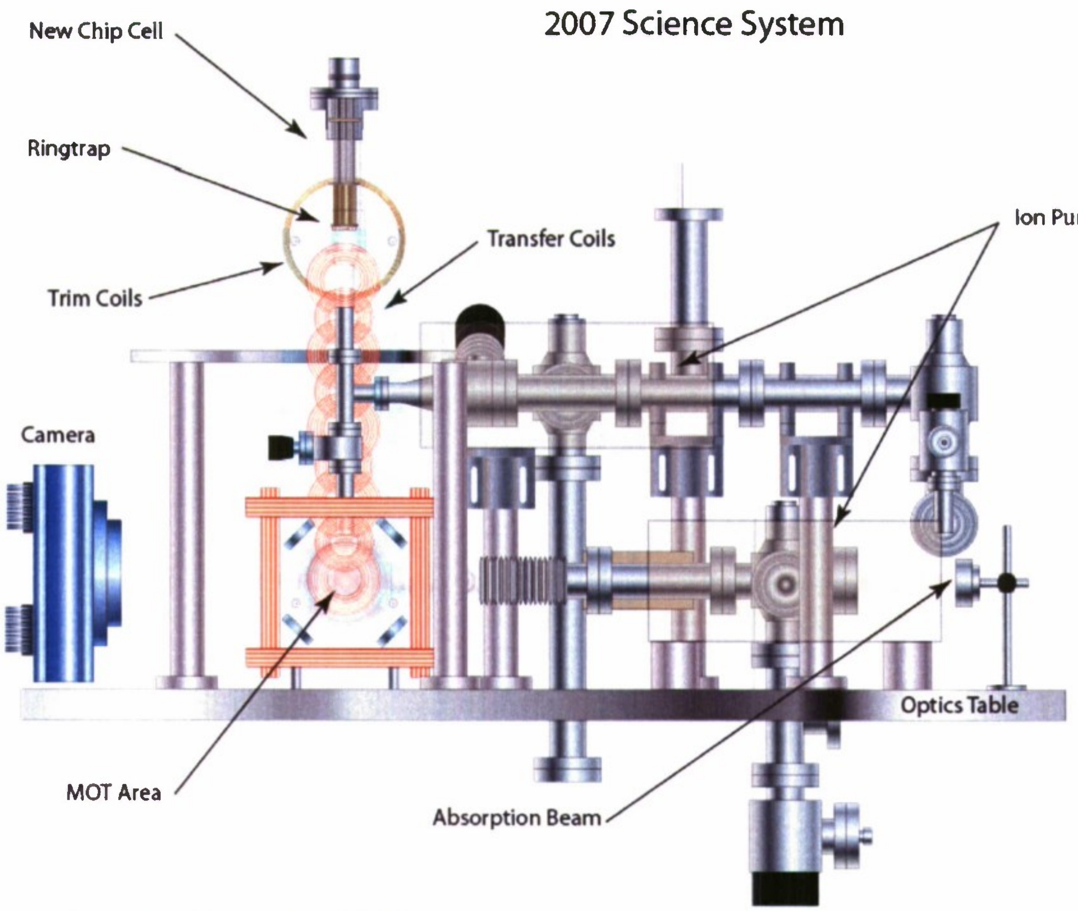

Figure 7. Science System as of Fall 2007.

The magnetic transfer coils are a series of anti-Helmholtz coil pairs cycled off and on to move the trapped atoms up. The atoms will be move from one set of overlapping coils to the next adiabatically until the cloud of atoms sits trapped just below the surface of the microchip. Next, in order to transfer as many cold atoms as possible into the waveguide the cold atom cloud is compressed and then transferred to a trap created by current running through wires in the configuration of an H that we call the H trap. This provides the ability to both move the atoms closer to the chip while compressing them further to match the waveguide produced by the U-Trap on the microchip. Finally, the current in the H trap will be turned off as the current in the microchip U trap is turned on. At this point the atoms will be solely confined by the currents from the microchip. This new chip cell allows our experimental area to maintain the low pressures we require with minimum complexity.

Figure 8. Assembled chip cell, (inverted), no chip attached, H trap is located below the thin film.

Developing and constructing the new chip cell allows us greater flexibility and quicker turn-around time for performing experiments. While developing the chip cell we also designed and fabricated four new chips that each examine different experimental concerns. We designed a 3-wire ringtrap that allows us to adjust the waveguide distance from the chip and at the same time adjust the trapping confinements. However, this chip does not allow the atoms to go completely around because being a single layer chip it does not avoid the leads. Though this chip was not designed as a functioning rotation sensor, it allows us to study loading, splitting and re-combination in a curved waveguide structure.

In addition to the 3-wire ringtrap we also developed and constructed a linear waveguide. This chip is currently installed in the new chip cell and will provide the simplest geometry while providing critical experimental information. The linear chip will be used to align and match the various transfers. Also this chip will allow us to align and work out the details of Bragg

Scattering, while we develop the next ringtrap microchip. Though this chip is simple in its design, it retains enough scientific complexity to provide a rich source of experimental investigation into atom interferometry.

Linear Waveguide Chip 4.2

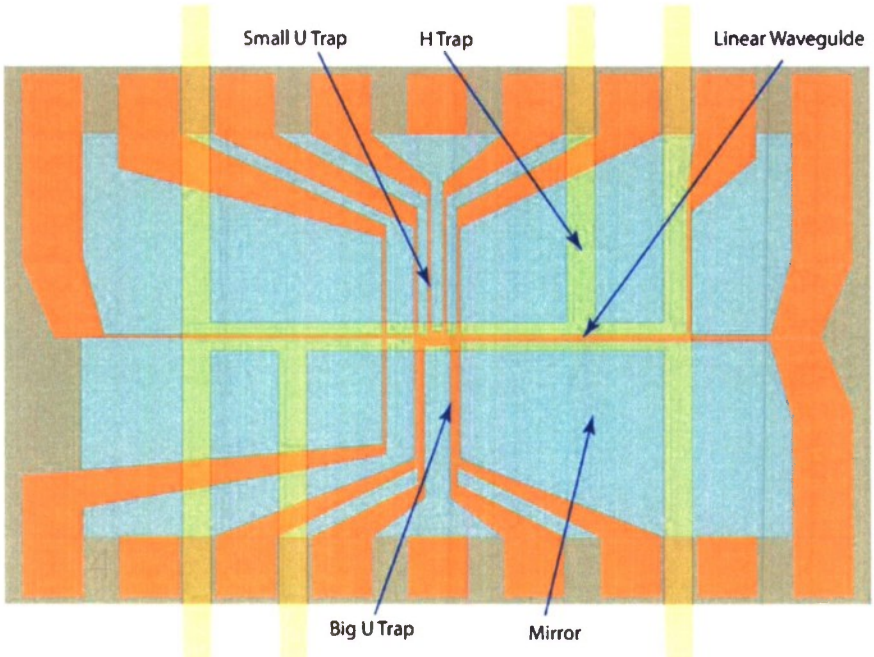

Figure 9. Linear Waveguide Microchip 4.2., shown with H Trap overlay.

We have recently begun constructing a chip that properly avoids the leads which is based upon this 3-wire design, thus studying this chip will provide us with the practical experience needed to progress. We anticipate leveraging the experience gained from the linear waveguide to the 3-wire waveguide. Splitting and re-combing atoms in a straight waveguide should prove easier to align as well as diagnose any technical details while avoiding any difficulties arising from the curvature of the 3-wire waveguide. Furthermore the 3-wire waveguide chip will give us a baseline from which to explore curvature effects when we move to a full ring-trap configuration. In addition, there are two other chips; one that allows radio frequency splitting in a linear waveguide and another that provides multiple functionality and includes wires for atomic clock operation as well as a continuous BEC transporter. These chips have been offered to one of our collaborators for their experiments at Oklahoma University.

4.2. 7-Wire Ringtrap Microchip

One of our latest achievements, which has a lot of promise, is the development of the n-wire ring-trap. This chip allows us to avoid the leads while providing control over the waveguide confinement, distance from the chip and the amount of radial curvature. This chip began as the a 7-wire ringtrap (see Figure 10), that is a 3-wire ringtrap and a 4-wire ringtrap interlaced.

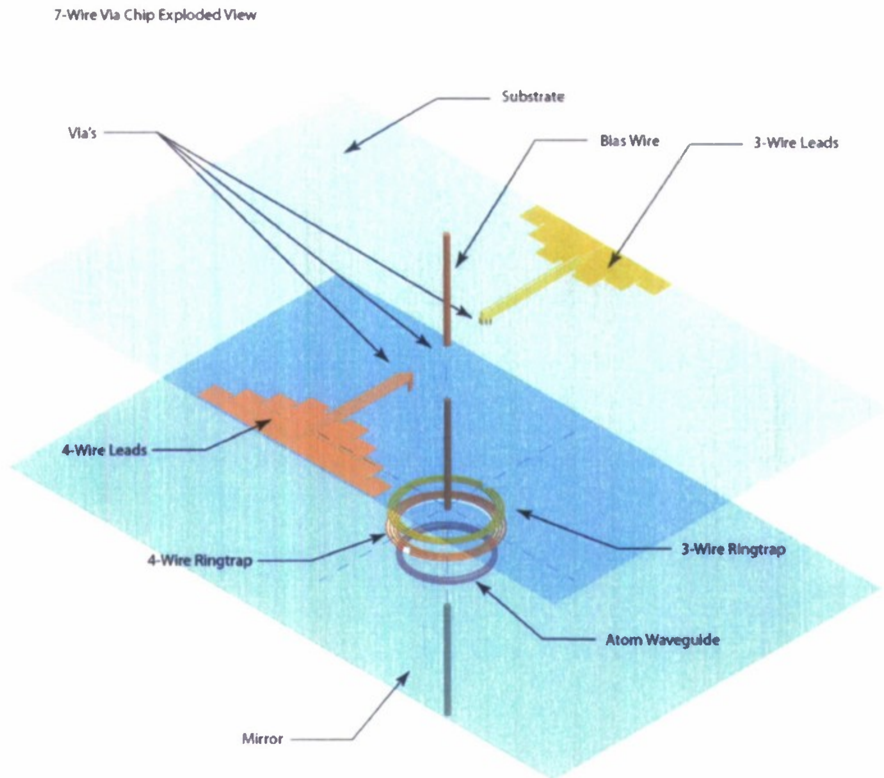

Figure 10. 7-Wire Ringtrap MicrochipExploded view.

The leads come through the back of the chip using vias and the operation of this device is similar to the original 4-wire off-axis ringtrap. However for this chip, all of the wires are on the same layer, See Figure 11.

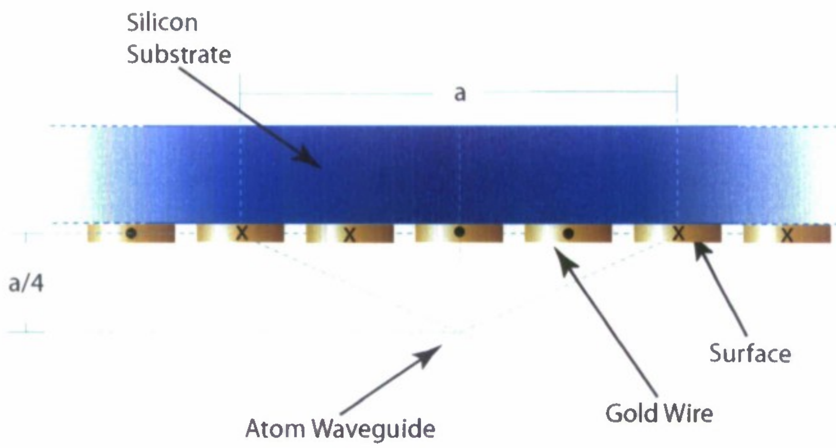

Figure 11. 7-Wire Ringtrap Microchip Cut-Away view.

We have modeled the 7-wire ringtrap extensively to ensure that we can avoid the issues we encountered with the 4-wire off-axis chip and built in as many adjustable parameters as possible. The 7-wire ringtrap will also give us the best chance for

making a functioning atom rotation sensor. Another compelling feature of the 7-wire ringtrap is that in principle more wires can be added providing the ability to change the radius dynamically. This might prove valuable for selecting appropriate ratios of radius/confinement. There is evidence that a lack of confinement in the waveguide can result in "betatron oscillations"[6]. This effect amounts to the atoms rolling up the sides of the waveguide and converting their longitudinal velocities into transverse oscillations. It is not know what effect this has on the rotation measurement and so it study will prove useful to understanding the physics of atom ringtrap gyroscopes.

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